Propagation and UWB Channel Characteristics on the Human Abdomen Area

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Abstract— In this paper, radio channel characteristics and signal propagation on the human abdomen area, in particular small intestine part, are evaluated by simulations. Studies are based on a recently published low ultra wideband cavity-backed antenna designed for in-body communications. The study is carried out with finite integration technique based electromagnetic propagation simulations. The main target of this study is to evaluate different antenna locations and antenna distances for the context of the wireless capsule endoscope localization. The study is carried out by evaluating frequency and time domain responses, as well as studying the strength of the E-fields and power inside the small intestine by introducing monitor points with different antenna location options. Furthermore, 2D power flow figures are used as to get insight to the power flow and to the propagation, in general, within the tissues. It is shown that channel characteristics and power flow vary significantly with frequency as well as with different antenna locations.

Index Terms— Directive antenna, finite integration technique, radio channel, signal propagation, wireless body area networks.

I. INTRODUCTION

Smooth transceiver algorithm design requires good knowledge of the radio channel characteristics. Thus, the propagation in the vicinity of the human body has been studied intensively for wireless body area networks (WBAN) applications. Especially, in-body propagation has recently been under the scope. However, modeling the radio propagation inside the human body is very challenging due to large variety of tissues having different sizes, dielectric properties, etc. \([1]-[7]\)

Developing and designing wireless capsule endoscopy (WCE) localization techniques requires comprehensive knowledge of the channel propagation around the human abdomen area. Several localization techniques have been presented for capsule endoscopy in the literature, \([8]-[11]\). One of the newest studies in this field is based on a system which estimates the location of the capsule by measuring the distance based on the round-trip propagation loss \([11]\). In the study, the transmitter antenna (Tx) and several receiver antennas (Rx) are placed on the human body. The location of the capsule in gastrointestinal (GI) tract is estimated by processing the received signals which have been reflected from the capsule.

In our study case, we focus on the similar antenna deployment case as in \([11]\), i.e. both antennas are placed on the body surface. The aim of this study is to evaluate channel characteristics on the human abdomen area with different antenna location options for the context of the WCE localization. The antenna location options are studied and compared in frequency and time domains. Furthermore, antenna location options are assessed for the context of WCE localization by studying the strength of the electric field through the propagation path from skin surface until the small intestine (SI).

This paper is organized as follows: Section II describes the study case of this paper, numerical results for channel characteristics are presented in Section III, E-field and power studies are shown in Section IV, and Conclusions are given in Section V.

II. STUDY CASE

A. Simulation scenario

Simulations were conducted by using Computer Simulation Technology (CST) MicroWaveStudio (MWS) 3D electromagnetic simulation software \([12]\). The software is based on the propagation prediction by solving Maxwell’s equations using finite integration technique (FIT) \([12]\). An anatomical voxel model Tom, presented in Fig. 1, is selected for the simulations since Tom has good resolution (0.5 mm x 0.5 mm x 0.5 mm) and it has all the necessary tissues on the abdomen area for our study case. In this study case, we focus on studying the channel characteristics in the abdomen area with on-body antennas designed for in-body communication \([13]\). To reduce the simulation time remarkably, we cut the voxel model significantly to include only the abdomen area of the voxel model and its surroundings for the simulations.

Figure 1. Anatomical voxel model Tom.
B. Low-band UWB Antenna

In this study, we use an ultra wideband on-body antenna designed for in-body communication. The antenna, which is recently presented in [13], is illustrated in Fig. 2. The antenna itself is originally an omnidirectional but with a cavity based approach, it becomes directional. This antenna property is favorable for capsule endoscope localization. The antenna is designed to work at the frequency band 3.74-4.25 GHz which meets the IEEE 802.15.6 standards requirements. More details of the antenna can be found in [13].

![Low-band UWB cavity-backed on-body antenna.](image)

Figure 2. Low-band UWB cavity-backed on-body antenna.

C. Antenna locations

Antenna locations on the abdomen area are selected to be suitable for capsule endoscope localization by taking into account the size of the antennas and coverage over the small intestine area. The aim is to study channel characteristics on different antenna locations and reflect the channel properties to the tissue content below the antenna.

The antenna location cases are presented in Fig.s 3 a-b. In the first antenna location option case, presented in Fig. 3a, the antennas are placed symmetrically side-by-side on the middle of the abdomen, just above the navel. In this case, the cavities are completely connected to each other, i.e., the distance between the antenna cavities is \(d=0\) cm; In this case, the distance between the antenna feeding points is 6.7 cm. The antenna-skin distance (\(d_s\)) is 3 cm, as proposed in [13]. In the second antenna location case, we evaluate the channel characteristics of the antenna location option 1 in a more realistic scenario for the context of capsule endoscopy localization by setting \(d_s=4\) mm. In the third case, presented in Fig. 3c, the separation distance \(d=2\) cm and \(d_s=4\) mm.

![Antenna location options, (a) 1-2 and (b) 3.](image)

Figure 3. Antenna location options, (a) 1-2 and (b) 3.

III. CHANNEL CHARACTERISTICS

In this section, channel characteristics of the antenna location options are represented in frequency and time domains. Firstly, reflection coefficients S11 and S22 are presented in Fig. 4 for the antenna location options 1-3. When comparing the S11 and S22 parameters of the antenna location option 1 and 2, we can see how the reflection coefficients deteriorates as we bring the antennas closer to the human body, as discussed in [13] with the layer model simulation results. Naturally, the reflection coefficients of the antenna location option 2 and 3 are relatively similar though some small changes can be seen due to different position respect to the tissues below. Interestingly, for each of the antenna location cases, there can be seen some differences between S11 and S22 parameters although all of the options are symmetrically located in the abdomen area respect to the vertical middle point. This is due to the differences in the tissues below the antenna 1 and antenna 2. Especially complex shape of small intestine causes significant differences between the tissues below the antenna 1 and antenna 2.

Next, the channel characteristics between the antennas 1 and 2 are evaluated in frequency domain. Fig. 5 presents channel responses S21, i.e. the path loss, for antenna location options 1-3. As expected, the channel is strongest for the antenna location option 1 for the most of the simulated frequency band. However, the antenna location 2 is stronger at the antenna’s operational frequency band. The weakest channel is obtained with the antenna location option 3, which is natural due to the gap between the antenna cavities. One can note that besides of the antenna’s operation frequency band 3.75-4.25 GHz, the channel gain is relatively strong around 2.5 GHz. This is explained due to the additional notches in the reflection coefficients at 2.5 GHz, as seen from Fig. 4.

Next, the frequency domain channel response S21 is converted into time domain using inverse fast Fourier transform (IFFT). The obtained impulse responses are presented in Fig. 6. The impulse response of the option 1 is the strongest, as expected from S21 response. Interestingly, the peaks of every antenna location option are at the same level at time range 2.5-3.5 ns, whereas at 3.5-4 ns the levels of the peaks of different options vary significantly.

![S11 and S22 parameters for different antenna location options.](image)

Figure 4. S11 and S22 parameters for different antenna location options.

![S21 parameters for different antenna location options.](image)

Figure 5. S21 parameters for different antenna location options.
IV. E-FIELD AND POWER STUDY

In this section, we evaluate how much the strength of the E-field changes on the propagation path from the skin surface through the small intestine. We located three electric field monitors (M1-M3) inside the voxel model below the antenna 1, as presented in Fig. 7. The figure depicts a crosscut of the voxel model from the z-direction (vertical coordinate of the voxel model). The first monitor (M1: (x,y,z)=45, 69.7, 196) is located immediately after the skin surface, the second (M2: (-45, 47.4 196)), is located in the fat tissue after the muscle layer, and the third (M3: (-45, 19, 196)) monitor is positioned in the middle point of the SI.

Fig.s 8a-c presents the strength of the E-field respect to the frequency at the monitor points for antenna location options 1-3, respectively. Evidently, the strength of the E-field is higher, the closer the monitor point is to the antenna. In the antenna location option 1, there is an interesting notch in the E-field of curve of the point M1 at the antenna’s operational frequency 4 GHz, which is assumed to be due to radiation patterns presented in [13]. Due to this notch, the difference between the E-field strength of M1 and M3 is only 10 dB with the antenna location options at 4 GHz. When taken into account the whole bandwidth 3.75–4.25 GHz, the difference between M1 and M3 is at maximum 25 dB. With the antenna location option 2-3, the difference between the E-field strengths in the frequency band of interest in approximately 25 dB. When comparing the E-field strengths of different antenna locations options at the operational frequency 4 GHz, it is noted that E-field strength is highest at evaluation points M1 and M2 with antenna location option 2, whereas there is no significant difference between E-field strengths of M3. However, at 3.75 GHz, the E-fields are strongest with antenna location options 2 and 3. Hence, it can be concluded that with these antenna location options the better view in the small intestine is obtained when the antennas are closer to the skin.

To have deeper insight on the losses within the tissues, we present power vectors respect Y-axis, along which the probes are settled, for different antenna location options 1-3 in Fig.s 8a-c, respectively. The figures include the power vector for frequencies 3.75 GHz, 4 GHz, and 4.25 GHz. Monitors points (M1-M3) are located in the y-axis for the clarity. One can clearly see the transition between the tissues in the power vectors: power is high on the skin surface as well as inside the skin and fat tissues after which it clearly diminishes when reaching the muscle layer. This is due to the fact that muscle layer is known to be challenging for the signal propagation caused by the high losses [15]. The power seem to be high again on the visceral fat tissue (y=48-50) before small intestine after which it dramatically decreases since SI is also known to be a tissue with high losses [15]. Fat is known to be a good propagation media among the human tissues due to low losses [3]. Thus, the power in the fat tissues shown in power vector plots is assumed to contain also signal power which has travelled through the fat tissue from wide area, for instance from the flanks. Interestingly, in all the antenna location options, the power level inside the small intestine is somewhat at the same level. The power is at highest with the frequency 3.75 GHz, which is understandable since the losses within the tissues increase as the frequency increase [3].

Finally, we study 2D power flows, which illustrate well the propagation within the tissues, in the abdomen area with different antenna location options. Fig.s 10a-c present 2D power flows for antenna location option 1 with frequencies 3.75 GHz, 4 GHz, and 4.25 GHz at the dB range 0–40 dB. Almost no difference can be seen in the power flow figures between the studied frequency and dB range in this case. The coverage of the small intestine area is quite similar in all the cases. Although we see frequency dependent E-field and power variations in the curves presented in Figs. 8 and 9, respectively, these variations are not significant enough to be visible in visual illustrations as shown, e.g. in Figs 10-11.

Instead, in the antenna location option 2, we can see more differences in the power flow presentations between the studied frequencies. At the 3.75 GHz, the signal propagates deeper in the abdomen tissues, whereas at f=4GHz and f=4.25 GHz, the signal propagates wider on the flank sides. In the antenna location option 3, the power flow figures are relatively similar for the cases f=3.75 GHz and f=4.25 GHz. In both cases, propagated signal does not reach the flanks at the determined dB range nor travels deep inside the abdomen tissues. Instead at f=4 GHz, the power is strong even in the first part of the inside abdomen tissues as well as abdomen coverage is wider. The differences between the power strength are due to differences in the propagation patterns, as presented in [13].
Figure 8a-c. Strength of the E-field respect to the frequency in M1 (red), M2 (black), and M3 (red) for the antenna location option 1, 2, and 3, respectively.

Figure 9a, b, c. Power for frequencies 3.75 GHz (red curve), 4 GHz (green curve), and 4.25 GHz (blue curve) for antenna location options 1, 2, and 3, respectively.

Figure 10a-c. 3D power flows for antenna location option 1 at 3.75 GHz, 4 GHz, and 4.25 GHz, respectively.

Figure 11a-c. 3D power flows for antenna location option 2 at 3.75 GHz, 4 GHz, and 4.25 GHz, respectively.
This paper evaluated the channel characteristics and propagation within the human abdomen area using a recently published cavity-backed on-body antenna designed for in-body communications, especially for capsule endoscopy localization. The main target of this study was to evaluate different antenna locations and antenna distances for the context of the wireless capsule endoscopy localization. The evaluation is carried out with studies on the S-parameters, time domain results, power flow analysis (both 1D and 2D) to understand differences in the power level and, in general, propagation within the tissues.

It is found that S-parameters and power flow behavior may vary significantly with different antenna location options. Even the small changes in the antenna location may have significant impact. Furthermore, there are clear changes in the power flows between different antenna location options. The presented results can be used in the research of the capsule endoscope localization, especially in the design of the antenna locations.

Future lines of this work will be oriented towards an exhaustive channel characterization using different antenna positions. The research will not be limited to the male voxel model, but also female and child models will be involved. Next work will be subject of a complete preliminary deep study to prepare for the on-body measurement trials (realistic cases).

IV. SUMMARY AND FUTURE WORK

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REFERENCES


Figure 12 a-b. 3D power flows for antenna location option 3 at 3.75 GHz, 4 GHz, and 4.25 GHz, respectively.